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This report summarizes an equipment and instrumentation system for high-speed digital image data acquisition and processing. The research program targets the physics of turbulence, mixing, and combustion, focusing on high-speed environments. The system includes components for Planar Laser Induced Fluorescence (PLIF), flame-speed, and ignition and extinction measurements of laminar flames at variable pressure; tracking flow structures in a high-speed mixing layer using high-speed color schlieren; laser-beam manipulation and volume scanning for three-dimensional turbulence measurements; and an expanded infrastructure capability for processing experimental and numerical-simulation data.

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HIGH-SPEED DIGITAL-IMAGE DATA ACQUISITION, PROCESSING, AND VISUALIZATION SYSTEM FOR TURBULENT MIXING AND COMBUSTION

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High-speed digital-image data acquisition, processing, and visualization system for turbulent mixing and combustion

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Abstract

This report summarizes an equipment and instrumentation system for high-speed digital image data acquisition and processing that was developed using the DURIP funds. The components of the system developed support the research program "Mixing, chemical reactions and combustion in high-speed turbulent flows," previously supported by AFOSR core-program Grant FA9550-04-1-0020, and presently by FA9550-07-1-0091, and the experimental part executed at Caltech of the AFOSR MURI research program, "Design, performance, and operation of efficient ramjet/scramjet combined-cycle hypersonic propulsion," under AFOSR Grant FA9550-04-1-0389. This combined program targets the physics of turbulence, mixing, and combustion, focusing on high-speed environments and applications.

The system includes components for Planar Laser Induced Fluorescence (PLIF), flame-speed, and ignition and extinction measurements of laminar flames at variable pressure; tracking flow structures in a high-speed mixing layer using high-speed color schlieren; laser-beam manipulation and volume scanning for three-dimensional turbulence measurements; and an expanded infrastructure capability for processing experimental and numerical-simulation data.

DURIP-acquired capabilities augmenting PLIF measurement technology were enabled with an Intensified CCD (ICCD) and associated data-acquisition components. Flame measurements rely on an extension of Particle Streak Velocimetry (PSV), using a new continuous-wave laser modulated with a Pockels cell. The measurements allow the study of laminar-flame profile details in higher-speed flames, such as encountered in ethylene and other fast fuels, increasing our understanding of flame structures and allowing extensive testing of chemical-kinetic models. The color schlieren measurements rely on a high-speed color CMOS camera and associated light-source and other support components. These measurements are providing new details of turbulent mixing in important flow geometries for both subsonic (diffusers) and supersonic (SCRAMJET) internal flows. The laser-beam manipulation and volume-scanning capability enabled by DURIP support is provided through a network of mirrors, servo actuators, motion controllers, and an optical scanner. This system enables resolved three-dimensional measurements of fully developed turbulence as a function of time. The processing and visualization of the data acquired with this system are enhanced through memory, CPU, and tape-backup upgrades to previously available data-acquisition and -visualization

computers. The experiments developed with this equipment provide a first look at the three-dimensional large-scale structure of turbulence and educate research students in disciplines important to the DOD mission.

1. Introduction

The initial proposal was predicated on a new technology for hybrid CCD-CMOS detectors that promised significant (×5) improvements in signal-to-noise ratio (SNR) of focal plane array (FPA) detectors. These detectors would have been developed and integrated into a next-generation image-acquisition system, based on an extension of spill-and-fill amplification technology in CMOS, in collaboration with iMagerLabs.

A detailed modeling and simulation effort to confirm the anticipated performance was undertaken following the DURIP award and prior to any commitment of funds and agreement with iMagerLabs. This initial effort resulted in an extension of understanding in these devices that revealed a flaw in the original thinking. We decided that these findings merited publication, and the work was submitted and published (Kern 2006).

In the exchange with Dr. Julian Tishkoff, our program manager, that ensued, we shared that the results of the new analysis made it inadvisable to follow the original plan and sought permission to investigate adapting Tunable Diode Laser Spectroscopy (TDLS), in collaboration with Zolo Technologies, for use in the AFOSR-supported experiments in the high-speed hydrogen-fluorine facility at Caltech. Several months of exchanges with Zolo, however, did not lead to an agreed-upon set of specifications for the part of the system they would deliver to Caltech. We sought and were granted a no-cost extension and proceeded with integrating our third choice, comprised of the system components described in this report.

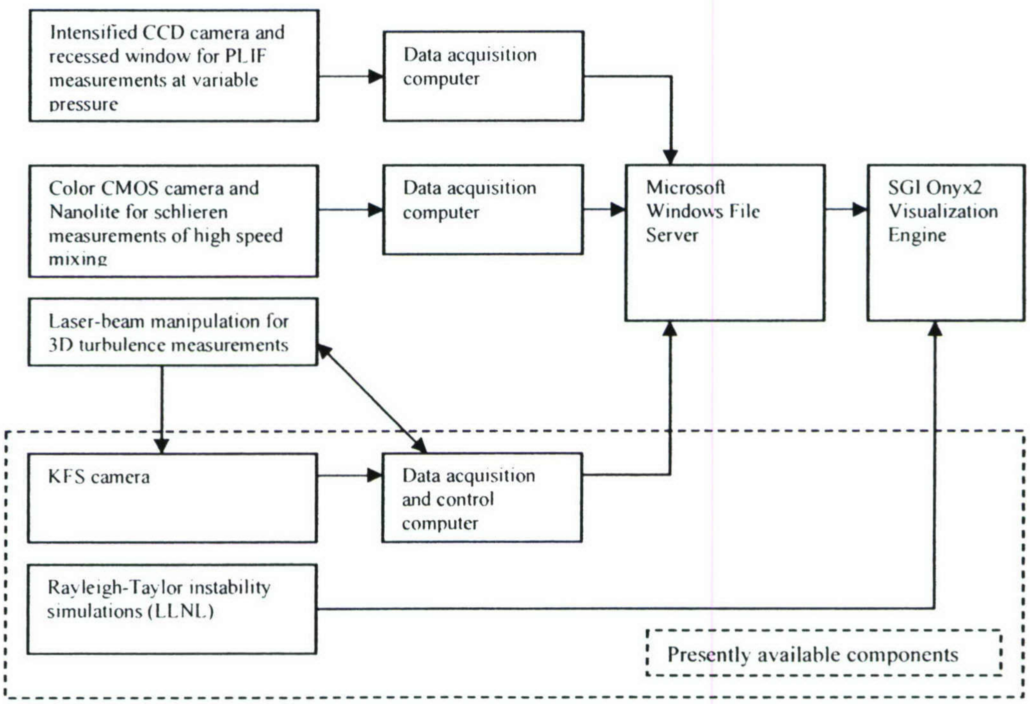

Fig. 1 Proposed system including presently available components

This report describes a high-speed digital-image data-acquisition and -processing system, as shown in Fig. 1. The system is intended to support research performed as part of the research program previously supported under AFOSR Grant FA9550-04-1-0020, and presently by FA9550-07-1-0091 and the experimental part executed at Caltech of the AFOSR MURI research program under Grant FA9550-04-1-0389. This program aims to increase knowledge of combustion at elevated pressures, mixing and combustion in high-speed flows, and the three-dimensional structure and dynamics of turbulence, turbulent mixing and variable-density turbulence. These issues are of interest to the Air Force, in the context of high-speed flows, both incompressible/subsonic, as well as compressible/supersonic. The latter, in particular, extend to fluid mechanics and chemical-kinetics issues that must be addressed if hydrocarbon-fueled, hypersonic-flight (SCRAMJET) vehicles are to become a reality.

Through research that the upgraded system is enabling, students and other researchers probe complex phenomena in turbulence, turbulent mixing, and combustion, gaining scientific and technical expertise in disciplines relevant to the DOD. Through experiments, the researchers will acquire experience in technologies including high-power laboratory fixed-wavelength and tunable-dye lasers; optics; digital imaging, high-speed data acquisition, processing, and visualization; and numerical methods.

To achieve these goals, a variety of experimental and computational resources are utilized. These resources include high-pressure combustion, supersonic shear-layer and turbulent-jet facilities, along with direct numerical simulations of complex flows, such as the Rayleigh-Taylor instability and other flows. The key diagnostic tools used in the experimental facilities rely on digital-imaging technologies, some developed in-house through AFOSR grants. The upgraded system extends the previously available capabilities in:

1. Hydrocarbon-flame measurements at variable pressure
2. High-speed digital color schlieren
3. Laser-beam manipulation
4. Data processing and visualization

These quantitative image-data capabilities and their impact on the AFOSR-supported research are discussed below.

2. Hydrocarbon-flame measurements at variable pressure

An increasingly large number of chemical-kinetic mechanisms are being proposed in the literature, each predicting a different flame behavior in various regimes traceable to differences in the modeled reactions and rate parameters chosen in each model. Although methane combustion is claimed to be well understood, our experiments have revealed discrepancies between accepted models and experiments, with significantly higher discrepancies for ethylene, for example, which only has one more carbon atom. To make progress towards a universal model of flame kinetics, our research on hydrocarbon flames provides a way to validate these mechanisms. Our research also extends the existing experimental database with high-accuracy simultaneous measurements of flame velocity and CH-radical axial profiles in a jet-wall-stagnation flow, in order to help mitigate the core imbalance between the hundreds of constants required in the model (several hundreds of reactions and more than 50 species are typically involved in such detailed kinetic mechanisms) and the low dimensionality of the small number of available data sets to validate the mechanisms. This imbalance leads to indeterminacies and non-uniqueness in the values of the constants used in the various kinetics models. Experiments currently are being carried out at 1 atm, and work continues on developing the capability for elevated pressure measurements (1 atm $< p <$ 12-15 atm).

Fuel blends of interest to scramjet propulsion, such as ethylene-hydrogen, are significantly more challenging experimentally, with peak velocities that are much higher (6 m/s for ethylene and 22 m/s for hydrogen, versus 3 m/s for methane). High-pressure environments are also troublesome because the flame thickness decreases with pressure, hence higher gradients and curvatures are encountered in high-pressure flames. Such flames present challenges that place them beyond the capabilities of the particle streak velocimetry (PSV) that was applied successfully to measure velocities in methane-air, ethane-air, and diluted ethylene-air flames so far.

To perform the PSV measurements, a continuous wave Argon-Ion laser operating at 2.5 W was used. The laser beam was chopped at a 50% duty cycle and at a maximal frequency of 2.4 kHz to illuminate the particles for a specified amount of time. The exposure on the CCD imager then produced streaks that were used to determine the local flow velocity. At the time the ICV technology was developed, this way to track particles represented the state of the art. PSV has the crucial advantage of significantly lower particle-loading requirements in this environment (2-3 orders of magnitude), compared to LDV or PIV. Low particle loading is critical in archival combustion measurements, where large particle loading may alter flame properties. Therefore, a new particle tracking velocimetry (PTV) technique was developed that keeps the low particle-loading advantage of PSV and features a higher spatio-temporal resolution, thanks to the use of both a new illumination source (Coherent Evolution-75 high repetition-rate Nd:YLF 527nm diode-pumped Q-switched laser with double-pulse option, cost: $140,360) and a new imaging system (high-resolution: 4008×2672 pix^2, low-noise (cooled), 14 bit dynamic range, Cooke PCO-4000 CCD camera with a maximum framing rate of 5 fps at full resolution, cost: $45,721).

The new higher resolution PCO-4000 camera enabled an increase in spatial resolution by a factor of 4 in the vertical direction, compared to the previous camera used, while keeping the noise at a low level. This camera has a double-exposure mode, so that PIV-type measurements are also possible. In order to be able to store continuously data to the disk at the same rate as the maximum framing rate of the camera, a designated Datawulf type computer system (total cost: $7,491) is used that is equipped with an Areca ARC1120 fast raid controller with 9 hard drives (necessary since a single disk drive is limited to around 20-30 MB/s transfer rate). A Matrox Helios camera interface board was chosen for its ability to transfer data quickly from the camera to the computer local RAM memory, and the Cooke Streampix software is used to manage data streaming. A Windows XP Pro 3-pack ($490) was purchased for the PCO-4000 control computer and for the two PCO-2000 control computers purchased the previous year, along with two 23-

inch HP L2335 widescreen monitors ($2566.65 total) that were purchased for the control computers (one monitor is shared between two computers using a KVM switch, cost: $43.25).

In parallel to progress on the imaging system, the illumination source was upgraded, since it was the most limiting factor in the PSV technique. The PSV spatio-temporal resolution is mostly limited by the chopping frequency, and the fastest chopping wheels available only go up to 3 kHz. On the other hand, the Evolution laser is officially capable of operation between 1 kHz and 10 kHz, when using its internal triggering. A careful and extensive testing of the Evolution laser, (only made possible after the purchase of with a field mate power meter from Coherent linked to a high energy sensor PM150-50, cost: $1,875, and a 100MHz Agilent oscilloscope (cost: $1,167.23) used to monitor the quality of the laser output pulses) , showed that the laser could be operated safely from between 1 kHz to 20 kHz with a higher accuracy in the repetition rate, when triggered externally by a Berkeley Nucleonics low-jitter digital delay and pulse generator (Model 565, cost: $5,000). The actual repetition rate was measured during the laser testing and is measured during experiments by a Thorlabs DET10A 200-1100 nm biased light detector (cost: $149). During laser testing, a mismatch between the diode current setpoint and the diode actual current was noticed. An Extech 380947 clamp-on current meter ($310) was acquired to measure currents inside the laser control box safely and locate the source of this discrepancy. This issue did not re-emerge following adjustments after these investigations.

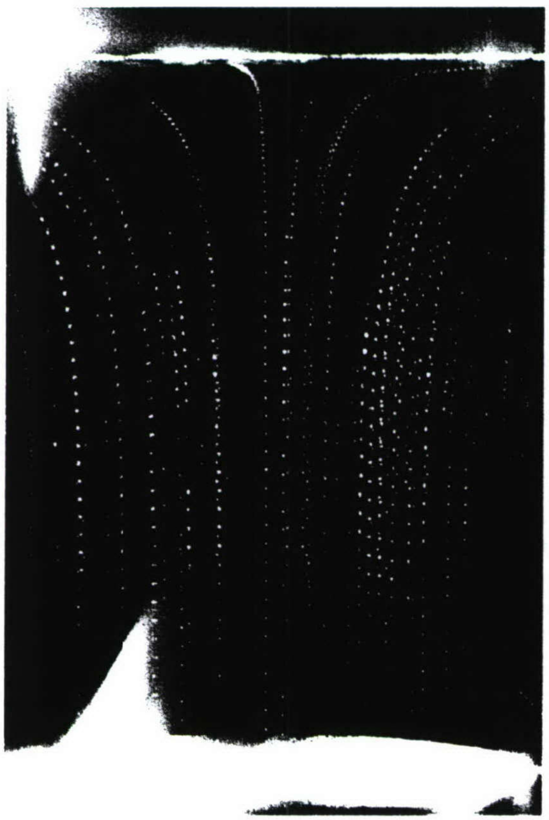

Figure 2: *Re* = 2524 impinging jet (laser repetition rate = 10 kHz).

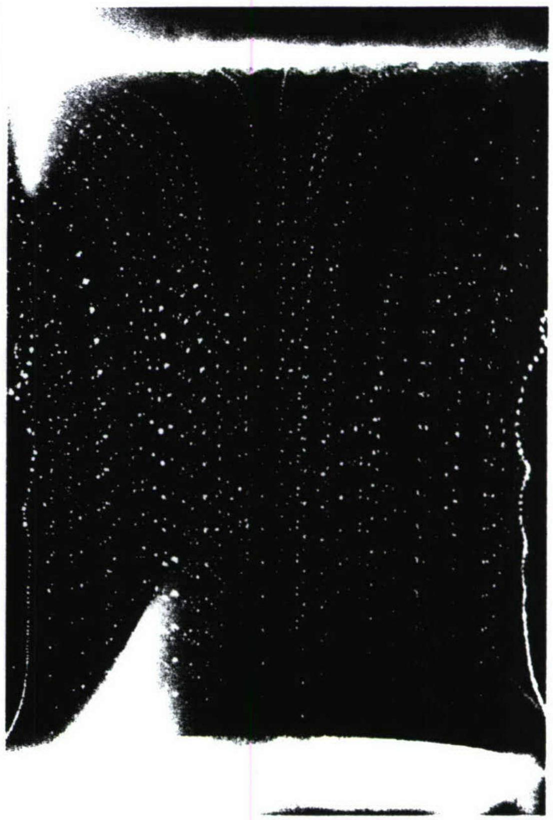

Figure 3: *Re* = 9120 impinging jet (laser repetition rate = 20 kHz).

To summarize, the Coherent Evolution laser system can operate at continuous repetition rates between 1 kHz and 20 kHz (more than 8 times higher temporal resolution than with the old PSV set-up), with 19.6 W-19.6 mJ/pulse, 69 W–13.8 mJ/pulse, and 26.9 W–1.3 mJ/pulse, at 1 kHz, 5 kHz, and 20 kHz, respectively, which is impressive compared with the 0.5 mJ/streak in the previous PSV technique at the maximum frequency of 2.4 kHz. This laser also can be used as a PIV light source, thanks to its double-pulse option. The delay between pulses ranges from 3 μs to 150 μs, which makes PIV-type velocity measurements possible.

Such high-energy pulses required new optical lenses and prisms with high damage thresholds, as well as a new beam dump, that were acquired using DURIP funds. A number of holders and translation stages were purchased from Optosigma, Newport, and Melles-Griot to integrate the new optical system.

Impinging jets were chosen to validate the new velocimetry technique. Particle Tracking Velocimetry (PTV) images were recorded (see sample images in Figs. 2 and 3), and the Bernoulli velocity, U_B, was determined from the static pressure drop, Δp, across the nozzle contraction at different Reynolds numbers, Re, according to the formula,

$$U_B = [2\,\Delta p\,/\rho\,/\,(1-(d/d_p)^4)]^{1/2}\,,$$

where $\rho = 1.2$ kg/m^3 is the density of the jet fluid (air), $d = 0.995$ cm is the diameter of the nozzle exit, and d_P=3.81 cm is the plenum internal diameter. For cold impinging jets, an error function represents the profiles (Bergthorson *et al.* 2005): $u(x)/U_\infty = \mathrm{erf}\,[\alpha\,(x/d - \delta/d)]$, where $u(x)$ is the axial velocity, U_∞ is suggested to be U_B, α is a strain-rate parameter, and x is the distance from the wall. δ/d is a scaled-offset length that is proportional to the scaled wall boundary-layer thickness and can be related to α, such that $\delta(Re, \alpha)/d = 0.755\,[Re\,\alpha]^{-1/2}$. Experiments were conducted at Reynolds numbers $Re \equiv U_\infty \rho\, d\,/\,\mu$ = 407, 708, 1409, 2524, 5049, and 9120, whereas the old PSV technique did not permit flows beyond $Re \approx 1400$ to be interrogated. $\mu = 1.84\times10^{-5}$ Pa.s is the dynamic viscosity of the jet fluid (air). The nozzle-to-plate separation distance (normalized by the nozzle diameter) is $L/d = 1.5$, so that the free jet regime (where the velocity is constant) is recovered. The error-function fits to the experimental data with the two free parameters U_∞ and α represent well the velocity data for all Reynolds numbers investigated (see the two samples on Figs. 4 and 5).

Figure 3 suggests that $Re = 9120$ is close to the limit of the diagnostic capabilities; however, a post-processing technique developed in-house yields results with very small scatter (Fig. 5). U_B is shown on these figures and is in agreement with U_∞ at all Reynolds numbers except the smallest ($Re = 407$), where the uncertainty in offset pressure is not negligible for such a low velocity. Table 1 shows the fit parameters and resulting rms errors $\epsilon_{rms.PTV}$.

The values of α_{PTV} are consistent with those reported in Bergthorson *et al.* (2005) for the low-Re range (see Table 2), where only one free parameter was used in the error-function fit (U_∞ was chosen equal to U_B). The superiority of the new PTV enabled by the DURIP support is clear when comparing $\epsilon_{rms.PTV}$ with $\epsilon_{rms.PSV}$. Scatter in the data decreased by a factor 2 at least in the PTV. Figure 6 shows the influence of Re on the fitted velocity profiles.

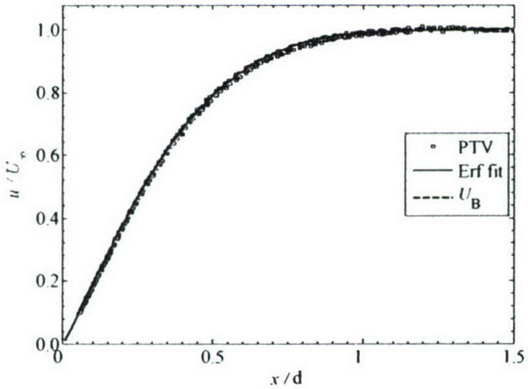

Figure 4: Comparison of error-function fit to experimental data at Re = 2524.

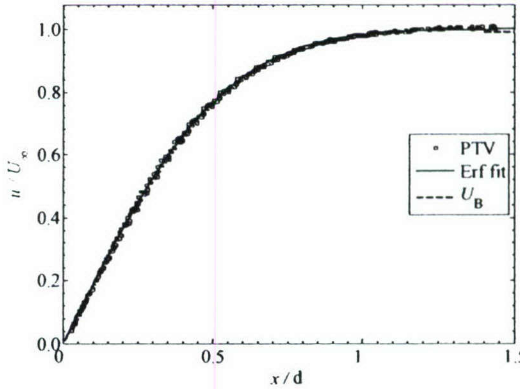

Figure 5: Comparison of error-function fit to experimental data at Re = 9120.

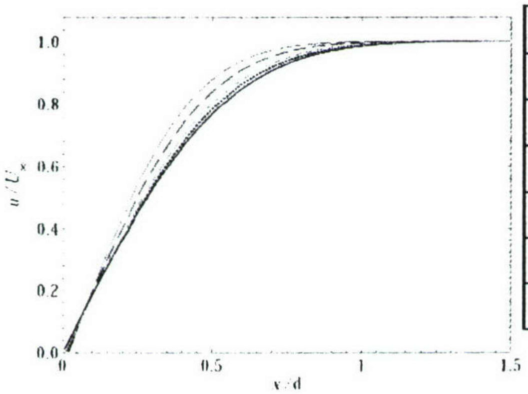

Figure 6: Influence of Re on the fitted velocity profiles: Re = 407 (long-dashed line), Re = 708 (medium-dashed line), Re = 1409 (dashed line), Re = 2524 (dotted line), Re = 5049 (dash-dotted line), Re = 9120 (solid line).

Re	α_{PTV}	U_∞	$\epsilon_{rms,PTV}/U_\infty$	$(U_\infty - U_B)/U_\infty$
407	2.28	0.63	0.011	-0.025
708	2.05	1.09	0.007	0.003
1409	1.85	2.17	0.008	0.004
2524	1.79	3.89	0.005	0.008
5049	1.74	7.78	0.008	0.007
9120	1.69	14.05	0.006	0.009

Table 1: Error-function fit parameters and rms error ϵ_{rms} of fits to experimental data.

Re	α_{PSV}	$\epsilon_{rms,PSV}/U_B$
400	2.21	0.017
700	2.00	0.010
1400	1.88	0.011

Table 2: Error-function fit parameter and rms error ϵ_{rms} of fits to experimental data. Extracted from Bergthorson et al. 2005.

Thanks to this new PTV technique, investigations of pure ethylene flames and blends of hydrocarbon fuel and hydrogen flames at atmospheric, as well as moderately high, pressures are now possible.

CH PLIF imaging also was upgraded thanks to the use of the new F/0.95 50mm C-mount DO-5095 Navitar lens ($951) that increased collected light by a factor 1.6 compared with the old F/1.2 Nikon lens. A 60% increase in collected light is significant in light-starved diagnostics.

Last, but not least, the simultaneous use of PTV with CH PLIF was enabled by the use of state-of-the-art optical filters. Specifically, a FF01-510/84 Semrock green band-pass filter (transmission >95% with 1% standard deviation between 467nm and 548nm, and $<10^{-4}$ % for wavelengths $\lambda < 457$ nm and $560 \text{ nm} < \lambda < 1017$ nm) is used in front of the PTV camera to reject the UV laser light (~390 nm) that excites the CH radicals, the fluorescence of the CH radicals (~430 nm), and some of the light coming from the C_2 Swan bands.

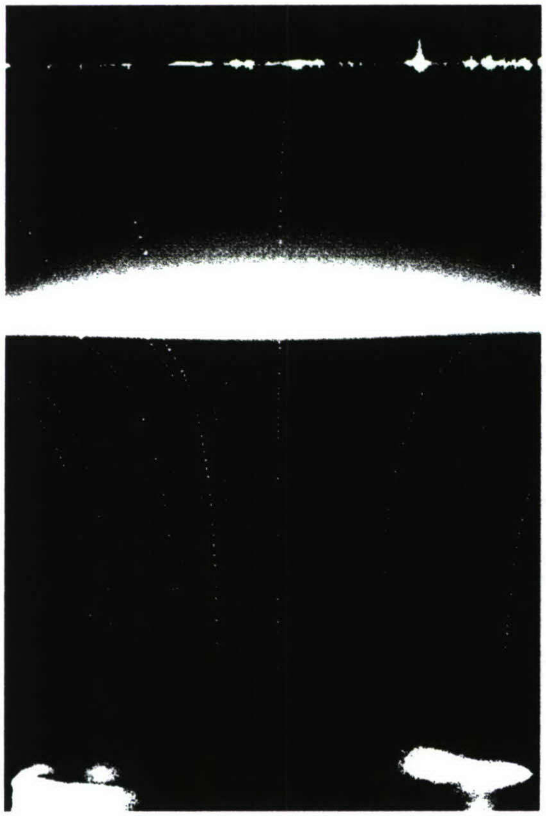

Figure 7: PTV picture of a $\Phi = 1.0$ methane-air flame taken with no optical filter.

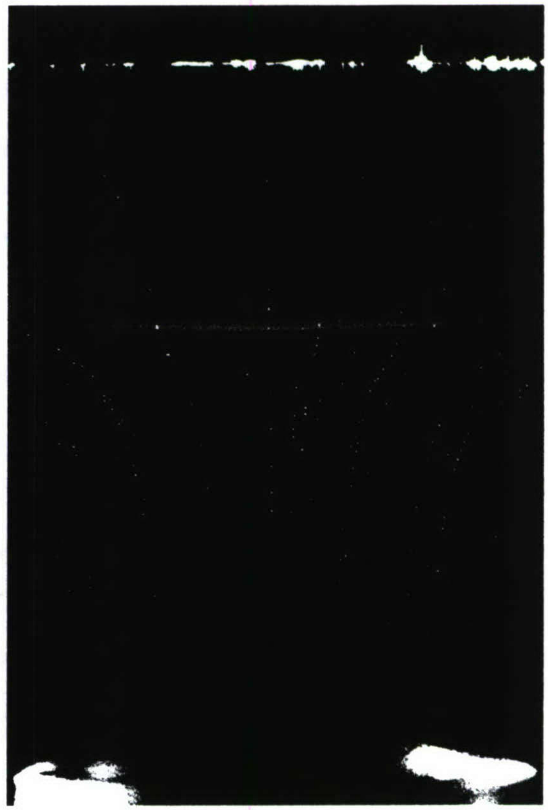

Figure 8: PTV picture of a $\Phi = 1.0$ methane-air flame taken with the green band-pass filter.

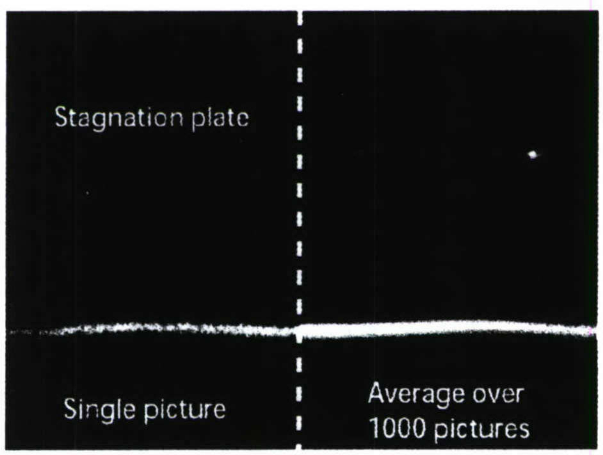

Figure 9: Sample CH PLIF images in a $\Phi = 1.0$ methane-air flame.

Figures 7 and 8 show how the new band-pass filter increases signal-noise ratio within the flame, enabling the resolution of the velocity profile even in that region. In front of the CH PLIF camera, a Schott KV-418 long-pass filter is used to reject the UV laser light (~390nm) exciting the CH radicals, and a NF01-532U Semrock notch filter (transmission $<10^{-4}$ % at 527nm, and >95% with 1% standard deviation between 400nm and 460nm) is used to reject the green light (527nm) used by the Evolution laser for the PTV while not decreasing the CH fluorescence signal. Two hot mirrors (1 for the PTV imaging, and the other one for the CH PLIF imaging) are placed between the optical filters and the flame in order to protect the filters (the significant amount of heat coming from the flame is reflected). Figure 9 shows how clean the CH PLIF signal is despite a large amount of green light (Evolution laser power of 8W) present in the field of view.

3. High-speed digital color schlieren

Funds were expended on upgrading the flow visualization system of the supersonic shear layer facility (S^3L). Research focuses on fundamental investigations of mixing and combustion, in turbulent, subsonic, and supersonic flows and is motivated by problems in high-speed air-breathing propulsion. Flow visualization, in the form of schlieren images, comprises a significant portion of the data acquired. As proposed, equipment was purchased to convert the existing low acquisition speed black and white schlieren visualization setup to high-speed color. The main advantage of a color coded schlieren system over traditional black and white knife-edge systems is that both the magnitude and direction of the light deflection can be measured.

The camera selected was the Phantom 7.3, manufactured by Vision Research. This camera has a 14-bit color CMOS sensor capable of frame rates up over 6.5 kfps (thousands of frames per second) at its full resolution of 800×600 pix^2 and over 190 kfps at reduced resolution. This camera cost $96,478.91.

To utilize the benefits of the high-speed camera fully, a new light source capable of delivering short-duration pulses at a high frequency was required. A Nanolite Flash Lamp driven by a Ministrobokin power supply, manufactured by High-Speed Foto Systeme of Germany, was selected. This light source is capable of delivering 18ns duration pulses at a frequency of up to 20 kHz for a total of 1000 pulses and cost $14,992.63.

Miscellaneous supplies were needed for the integration of the light source and camera. A number of lenses, filters, holders, translation stages and optical breadboards were purchased in order to achieve the required optical setup for the flow visualization. Components were selected from three leading manufacturers, Newport Corporation, Edmund Optics, and OptoSigma, for a total cost of $5,435.91. A digital delay generator was purchased to synchronize the pulse from the light source to the trigger of the camera. The delay generator was purchased from Berkeley Nucleonics for $3,201.90.

Finally, new optical windows were purchased for the S^3L. One of the combustion products present in the facility is HF, which is used in industry for glass-etching applications. Consequently, the quality of the existing windows had significantly degraded over the two decades of operation of the facility, meriting replacement. The manufacturer selected, Red Optronics, provided the windows for $2.998.94.

Total expenditures for this part of the project were $123,108.29.

4. Laser beam manipulation

Some optics were also purchased for and integrated into the scalar-dispersion experiment. The optical setup is designed to take the output of a 200 Hz YAG laser, spread it into a sheet, and step the sheet in depth between the laser pulses. Additionally, a 22" diameter parabolic mirror collimates the laser sheets so they are parallel within the test section. A set of cylindrical lenses ($194.43) was purchased to generate the laser sheet. A set of high-powered laser mirrors ($437.18), long distance focusing lenses ($165.51), and lens mounts ($331.95) also were purchased for this purpose. The Aeronautics machine shop fabricated the mount for the parabolic mirror ($1,100) and additional mounts for the other optical components ($300). Some photomicrosensors were purchased for position sensing ($242.23) as well. Finally, a special camera was purchased for monitoring laser beam quality ($1834.09).

5. Data processing and visualization

In order to facilitate the recording and transfer of large amounts of data, the current network (100 Mb/s – megabit/second) required upgrading to 1 Gb/s (gigabit/second) with trunking to allow transfer rates of up to 4Gb/s (four 1 Gb/s lines trunked together). For this network upgrade, a pair of Dell Powerconnect 6024F gigabit optical fiber switches ($4,889.87) and 3 Dell Powerconnect 5234 gigabit copper switches ($2,432.38) were purchased. Also, a 12-strand (6-pair) fiber-optic cable was purchased to connecting the computer room to the labs ($1,404.19). Finally, an uninterrupted power supply (UPS) was purchased to provide backup power for the switches & server computers ($958.66)

6. Conclusions

While, as a result of extensive modeling and simulation efforts, it was decided not to attempt to implement the original proposal, equipment acquired under the DURIP grant sponsorship has enabled considerable advances in combustion, high-speed flow, and multi-dimensional turbulence measurements in regimes hitherto unreachable with previous instrumentation. New experiments and measurements based on this instrumentation are presently in progress under AFOSR sponsorship.

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[1] Starting 29 January 2006.

[2] Through 31 May 2005.